

Rec # 550772

28
EX A -

UNITED STATES DISTRICT COURT
FOR THE EASTERN DISTRICT OF MICHIGAN
SOUTHERN DIVISION

IMRA AMERICA, INC., a Michigan
corporation,

Plaintiff,

v.

IPG PHOTONICS CORPORATION, a
Delaware corporation,

Defendant.

Case: 2:06-cv-15139

Assigned To: Taylor, Anna Diggs

Referral Judge: Majzoub, Mona K

Filed: 11-16-2006 At 03:16 PM

CNP ~~IPG~~ IMRA AMERICA VS IPG PHOTONICS C
ORP (LE)

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JURY TRIAL REQUESTED

Attorneys for Plaintiff, IMRA AMERICA,
INC.

COMPLAINT FOR PATENT INFRINGEMENT

Plaintiff IMRA AMERICA, INC. ("IMRA"), for its Complaint against Defendant IPG PHOTONICS, CORPORATION ("IPG"), hereby alleges as follows:

I. JURISDICTION AND VENUE

1. This is an action for patent infringement under 35 U.S.C. §§ 271 and 281.
2. This Court has subject matter jurisdiction under 28 U.S.C. §§ 1331 and 1338(a) because this action arises under the Patent Laws of the United States, Title 35 of the United

States Code, Sections 100 *et seq.*

3. Venue is proper in this Judicial District under 28 U.S.C. §§ 1391 and 1400.

II. THE PARTIES

4. IMRA is a corporation organized and existing under the laws of the State of Michigan and has a principal place of business at 1044 Woodridge Avenue, Ann Arbor, MI 48105.

5. IMRA is informed and believes, and thereon alleges, that IPG is a Delaware corporation that has a place of business at 50 Old Webster Road, Oxford, Massachusetts, 01540 and that does business within this Judicial District.

6. IMRA is informed and believes, and thereon alleges, that IPG has committed the acts alleged herein within this Judicial District.

III. CLAIM FOR RELIEF

7. IMRA hereby repeats, re-alleges and incorporates by reference paragraphs 1-6 of this Complaint as though fully set forth herein.

8. On October 6, 1998, the United States Patent and Trademark Office duly and legally issued United States Patent No. 5,818,630 ("the '630 Patent"), entitled "Single-Mode Amplifiers and Compressors Based on Multi-Mode Fibers" and naming Martin E. Fermann and Donald J. Harter as inventors. IMRA is the owner by assignment of all right, title and interest in the '630 Patent. A copy of the '630 Patent is attached hereto as Exhibit A.

9. IMRA is informed and believes, and thereon alleges, that IPG, through its agents, employees and servants, has knowingly, intentionally and willfully infringed the '630 Patent by making, using, offering for sale, selling and/or importing fiber amplifiers covered by one or more claims of the '630 Patent.

10. IMRA is informed and believes, and thereon alleges, that IPG, through its agents, employees and servants has induced infringement and/or engaged in acts of contributory

infringement of the '630 Patent.

11. IPG committed these acts of infringement without license or other authorization from IMRA.

12. IPG's infringement has damaged IMRA in an amount not yet fully known to IMRA.

13. Unless IPG is enjoined by this Court, IPG will continue to infringe the '630 Patent in violation of IMRA's rights, causing great and irreparable injury to IMRA, for which IMRA has no adequate remedy-at-law.

WHEREFORE, IMRA prays for relief as follows:

A. That IPG be adjudged to have infringed United States Patent No. 5,818,630;

B. That IPG, its officers, agents, servants, employees, and attorneys, and those persons in active concert or participation with them who receive actual notice of the Order, be permanently restrained from infringing or actively inducing others to infringe United States Patent No. 5,818,630;

C. That IPG account for damages to IMRA for its infringement of United States Patent No. 5,818,630;

D. That a judgment be entered against IPG awarding IMRA all damages proven at trial, and in no event less than a reasonable royalty, for infringement of United States Patent No. 5,818,630;

E. That the damages in this judgment be trebled for IPG's knowing, intentional and willful infringement of United States Patent No. 5,818,630;

F. That there be an assessment of pre-judgment and post-judgment interest and costs against IPG and in favor of IMRA, and an award of this interest and costs to IMRA;

G. That this be judged an "exceptional" case within the meaning of 35 U.S.C. § 285,

and that IMRA be awarded its attorneys' fees pursuant thereto, recoverable from IPG; and

H. That IMRA receive such other and further relief as the Court may deem just and proper.

Respectfully submitted by,

DICKINSON WRIGHT PLLC

Dated: November 16, 2006

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DEMAND FOR TRIAL BY JURY

Pursuant to Rule 38(b) of the Federal Rules of Civil Procedure, Plaintiff IMRA AMERICA, INC. hereby demands trial by jury in this action for all issues so triable.

Respectfully submitted by,

DICKINSON WRIGHT PLLC

Dated: November 16, 2006

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A.



US005818630A

United States Patent [19]

Fermann et al.

[11] **Patent Number:** **5,818,630**[15] **Date of Patent:** **Oct. 6, 1998**[54] **SINGLE-MODE AMPLIFIERS AND COMPRESSORS BASED ON MULTI-MODE FIBERS**[75] Inventors: **Martin E. Fermann; Donald J. Harter**, both of Ann Arbor, Mich.[73] Assignee: **Imra America, Inc.**, Ann Arbor, Mich.[21] Appl. No.: **882,349**[22] Filed: **Jun. 25, 1997**[51] Int. Cl.⁶ **H01S 3/08; H01S 3/10**[52] U.S. Cl. **359/341; 359/116; 359/340; 372/19**[58] Field of Search **359/116, 134, 359/160, 340, 341; 385/10, 28; 372/6, 19**[56] **References Cited****U.S. PATENT DOCUMENTS**

3,808,549	4/1974	Maurer .	
4,913,520	4/1990	Kafka .	
5,187,759	2/1993	DiGiovanni et al. .	
5,349,602	9/1994	Mehouys et al.	359/344
5,499,134	1/1996	Galvanuskas et al. .	
5,513,196	4/1996	Bischel et al.	372/19

OTHER PUBLICATIONS

Poole et al, Fabrication of Low-Loss Optical Fibres Containing Rare-Earth Ions, *Optics Letters*, vol. 22, pp. 737-738 (1985).

D. Tavernier et al, "158 μ J Pulses From a Single-Transverse-Mode, Large-Mode-Area Erbium-Doped Fiber Amplifier", *Optics Letters*, vol. 22, No. 6, pp. 378-380, Mar. 15, 1997.

L. Yang et al, "Chirped-Pulse Amplification of Ultrashort Pulses with a Multimode Tm:Zblan Fiber Upconversion Amplifier", *Optics Letters*, vol. 20, No. 9, pp. 1044-1046, May 1, 1995.

U. Griebner et al, "Efficient Laser Operation with Nearly Diffraction-Limited Output from a Diode-Pumped heavily Nd-Doped Multimode Fiber", *Optics Letters*, vol. 21, No. 4, pp. 266-268, Feb. 15, 1996.

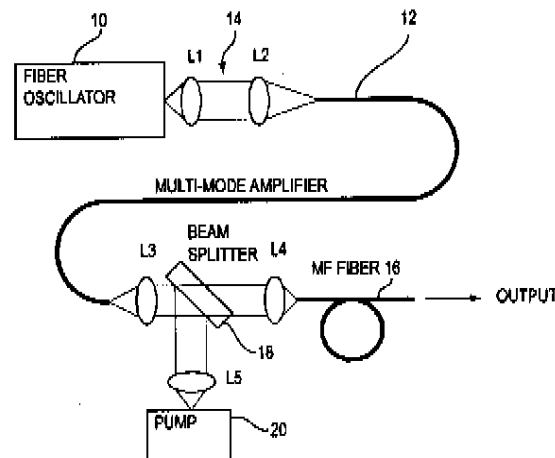
T. Strasser et al, "Reflective-Mode Conversion with UV-Induced Phase Gratings in Two-Mode Fiber", *Optical Fiber Comm., Conf.*, vol. 2, 1996, pp. 348-349.

W. Gambling et al, "Pulse Dispersion for Single-Mode Operation of Multimode Cladded Optical Fibres", *Lett., Elect. Lett.*, vol. 10, pp. 147-149, May 2, 1974.

(List continued on next page.)

Primary Examiner—Nelson Moskowitz.*Attorney, Agent, or Firm*—Sughrue, Mion, Zinn, Macpeak & Seas, P.C.[57] **ABSTRACT**

To amplify and compress optical pulses in a multi-mode (MM) optical fiber, a single-mode is launched into the MM fiber by matching the modal profile of the fundamental mode of the MM fiber with a diffraction-limited optical mode at the launch end. The fundamental mode is preserved in the MM fiber by minimizing mode-coupling by using relatively short lengths of step-index MM fibers with a few hundred modes and by minimizing fiber perturbations. Doping is confined to the center of the fiber core to preferentially amplify the fundamental mode, to reduce amplified spontaneous emission and to allow gain-guiding of the fundamental mode. Gain-guiding allows for the design of systems with length-dependent and power-dependent diameters of the fundamental mode. To allow pumping with high-power laser diodes, a double-clad amplifier structure is employed. For applications in nonlinear pulse-compression, self phase modulation and dispersion in the optical fibers can be exploited. High-power optical pulses may be linearly compressed using bulk optics dispersive delay lines or by chirped fiber Bragg gratings written directly into the SM or MM optical fiber. High-power cw lasers operating in a single near-diffraction-limited mode may be constructed from MM fibers by incorporating effective mode-filters into the laser cavity. Regenerative fiber amplifiers may be constructed from MM fibers by careful control of the recirculating mode. Higher-power Q-switched fiber lasers may be constructed by exploiting the large energy stored in MM fiber amplifiers.

49 Claims, 10 Drawing Sheets

5,818,630

Page 2

OTHER PUBLICATIONS

W. Gambling et al, "Mode Conversion Coefficients in Optical Fibers", Applied Optics, vol. 14 No. 7, Jul. 1975.
D. Gloge, "Optical Power Flow in Multimode Fibers", Bell System Technical Journal, vol. 51, pp. 1767-1783, May 8, 1972.
D. Harter, "Alexandrite-Laser-Pumped Cr³⁺: BaF₂", Optics Letters, vol. 17, pp. 1512-1514, Apr. 3, 1992.
M. Nisoli et al, "Generation of High-Energy 20 fs Pulses by a New Compression Technique", Cleo 91, paper CTuR5, pp. 189-190 (1996).

D. Marcus, "The Theory of Dielectric Optical Waveguides", pp. 238-239, Academic Press, (1974).

Waliano et al, Appl. Phys. Lett., vol. 63, #5, pp. 580-582, Aug. 2, 1993.

Luther et al, Louis. Opt. Soc. of America, B, vol. 7, 1907, pp. 1216-1220, Jul. 1990.

Fermann et al, Proc. 1995 Opt. Fiber Commun. Conf., IEEE, pp. 39-40, Feb. 27, 1998.

Nybolah et al, IEEE Photonics Tech. Lett., vol. 31, #12, Dec. 1991, pp. 1079-1081.

U.S. Patent

Oct. 6, 1998

Sheet 1 of 10

5,818,630

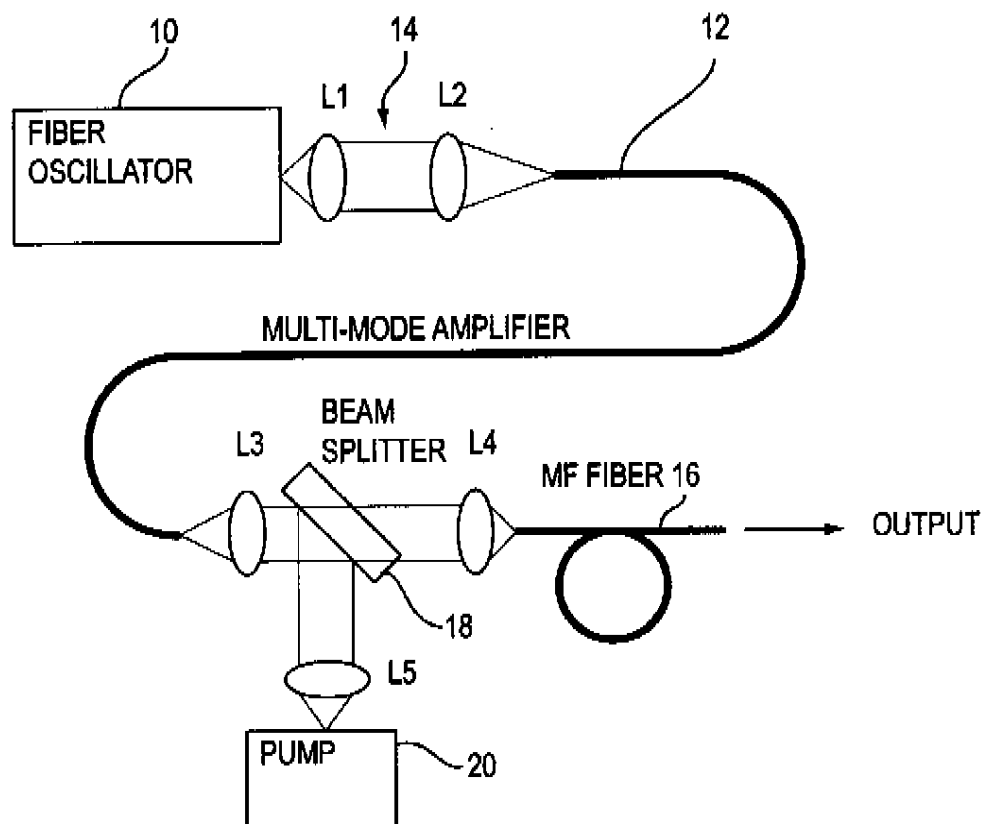


FIG. 1

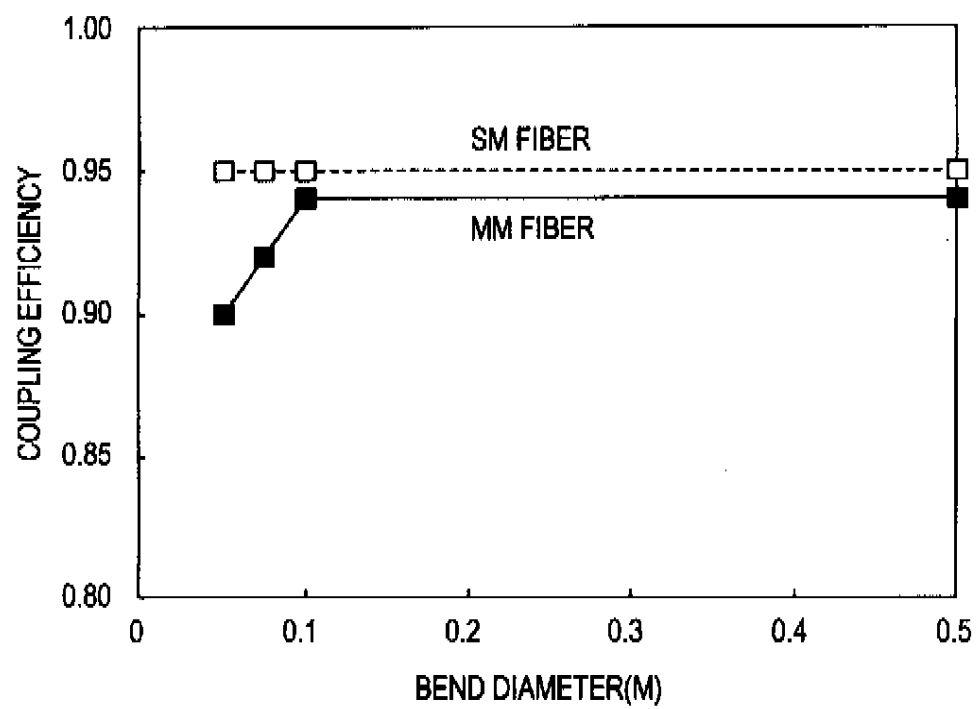
U.S. Patent

Oct. 6, 1998

Sheet 2 of 10

5,818,630

FIG. 2



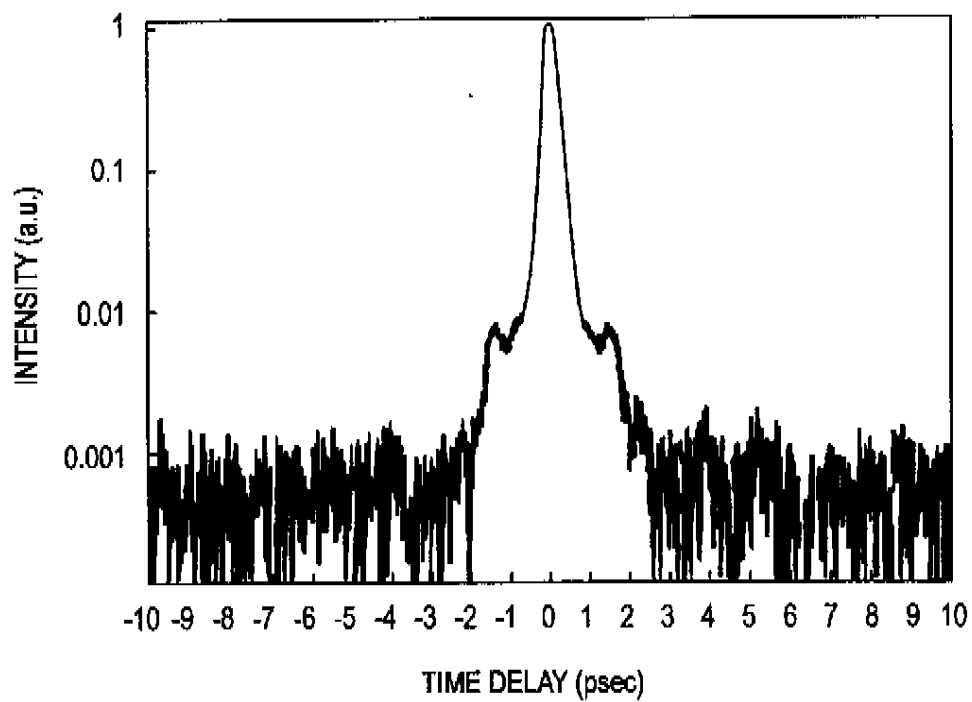
U.S. Patent

Oct. 6, 1998

Sheet 3 of 10

5,818,630

FIG. 3



U.S. Patent

Oct. 6, 1998

Sheet 4 of 10

5,818,630

FIG. 4

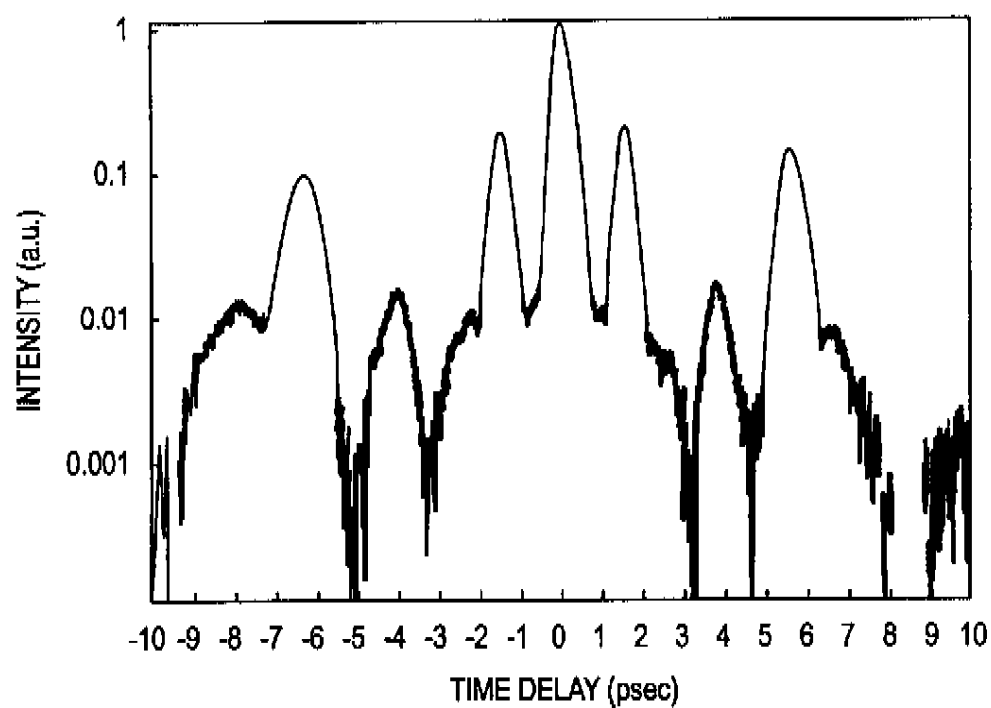


FIG. 5

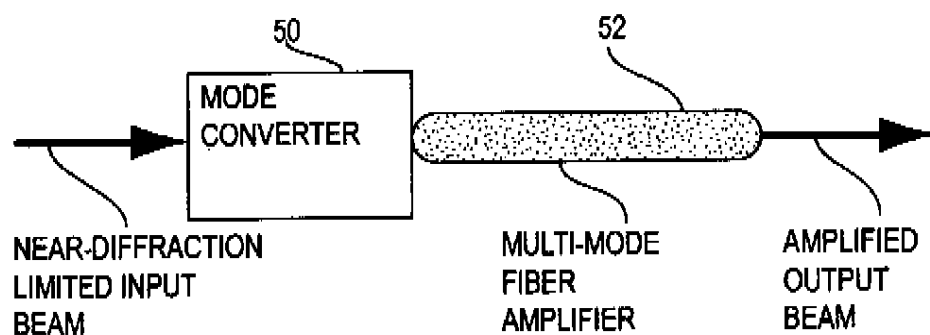
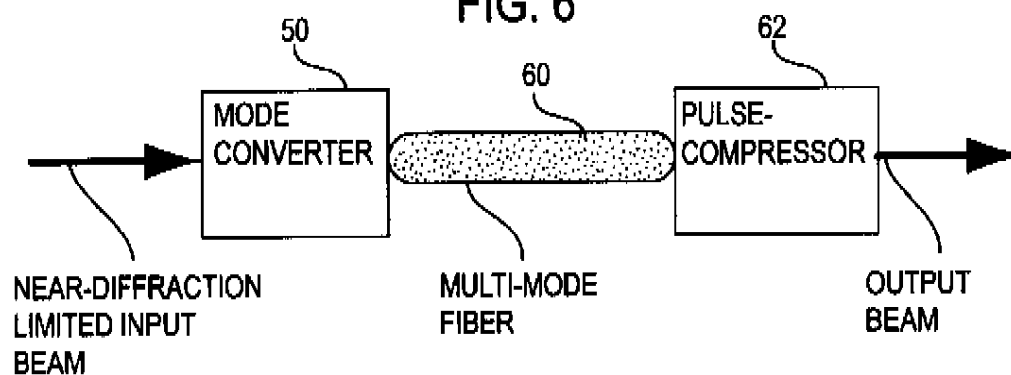


FIG. 6



U.S. Patent

Oct. 6, 1998

Sheet 6 of 10

5,818,630

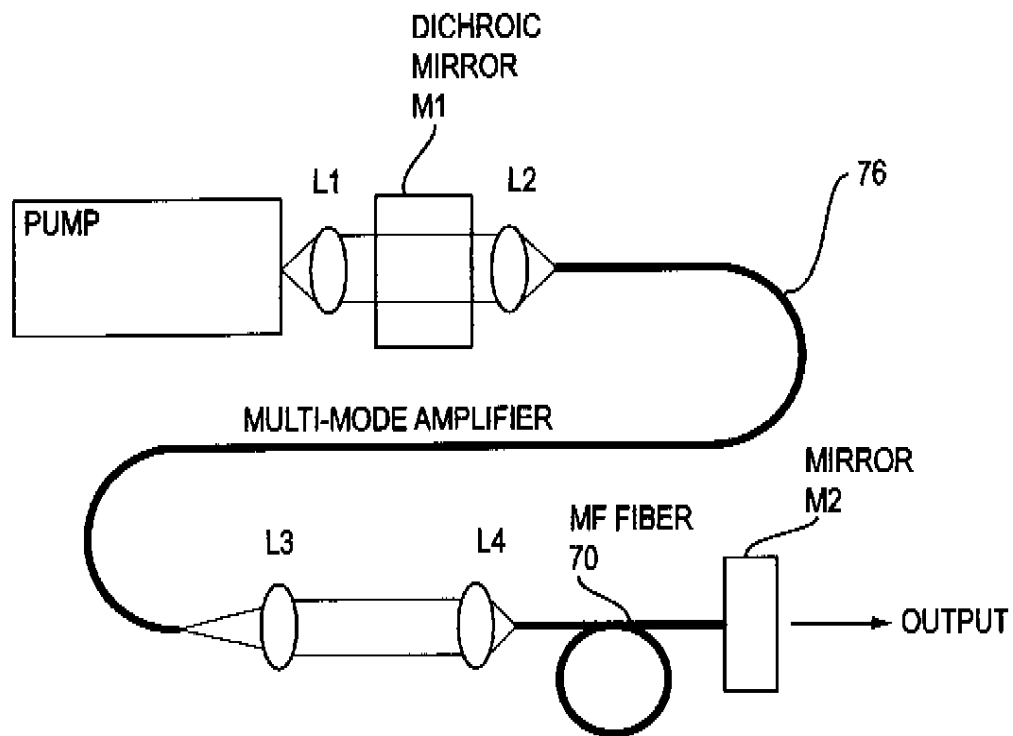


FIG. 7

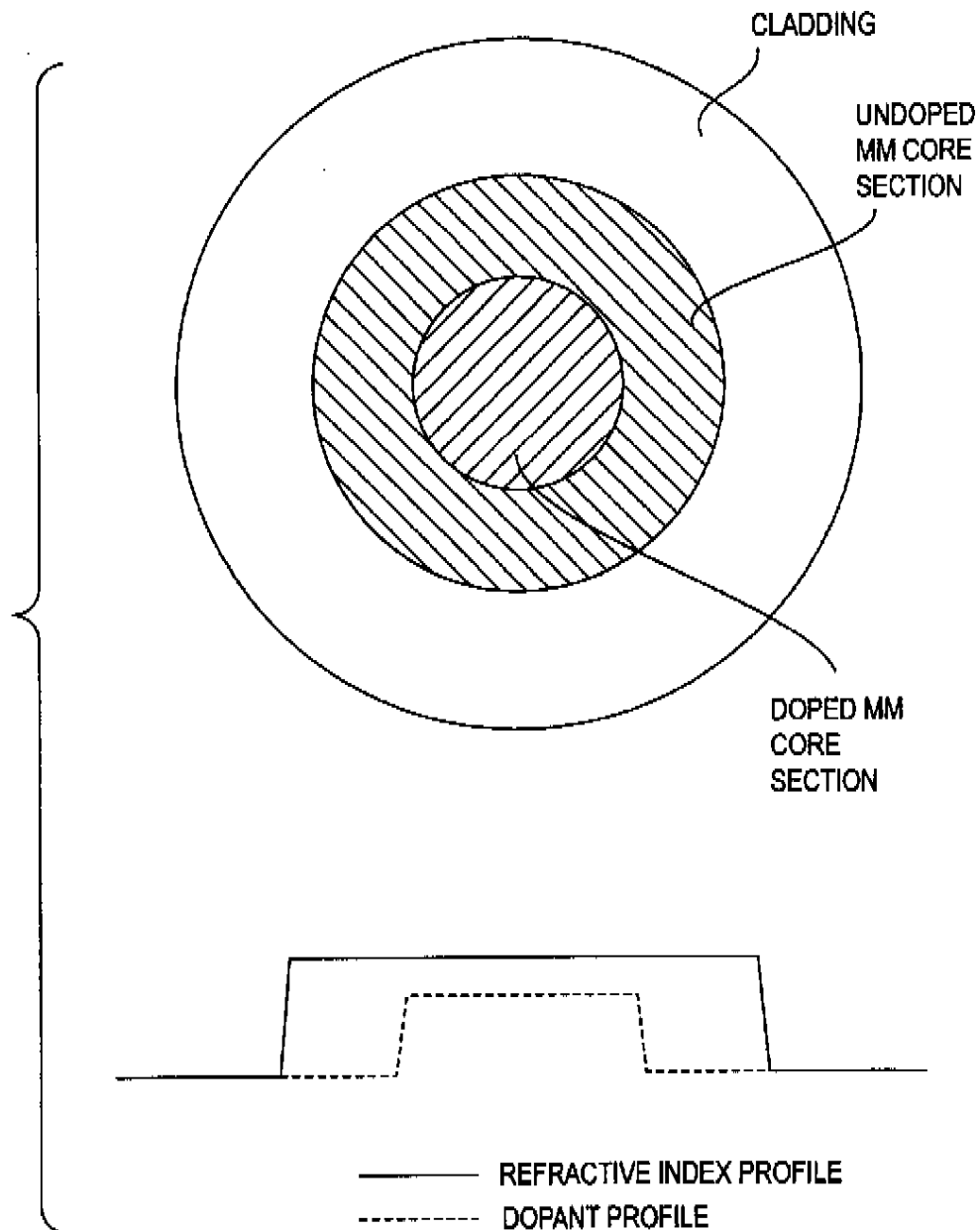
U.S. Patent

Oct. 6, 1998

Sheet 7 of 10

5,818,630

FIG. 8



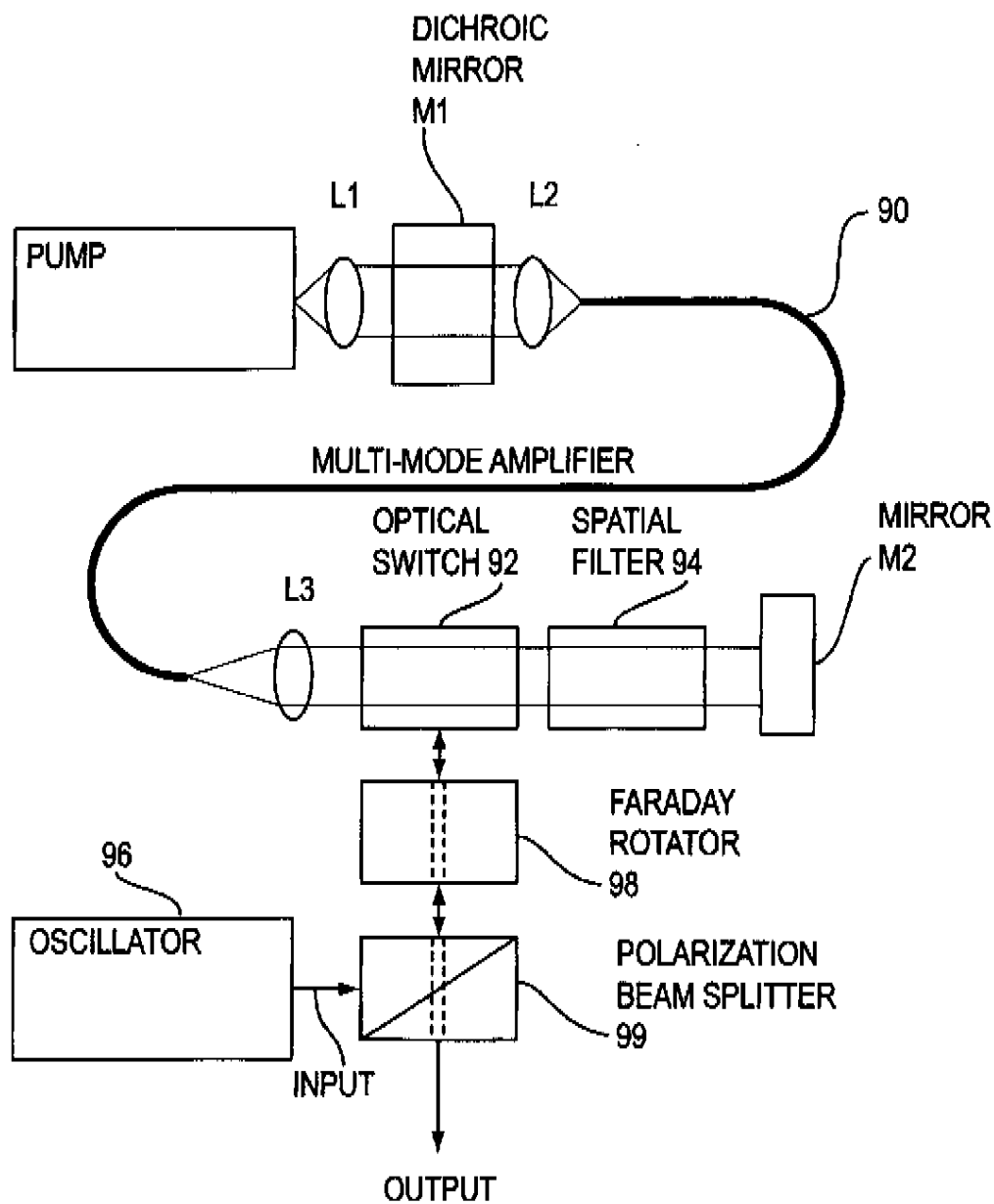
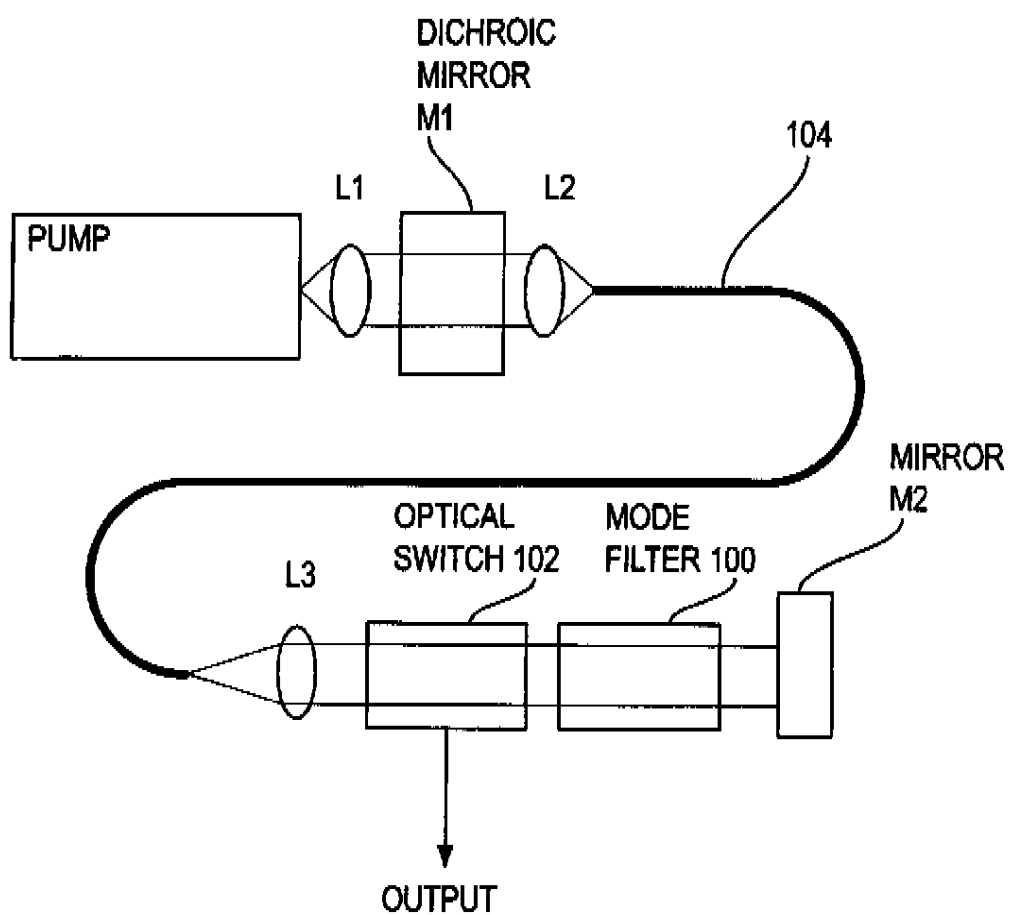


FIG. 9

FIG. 10



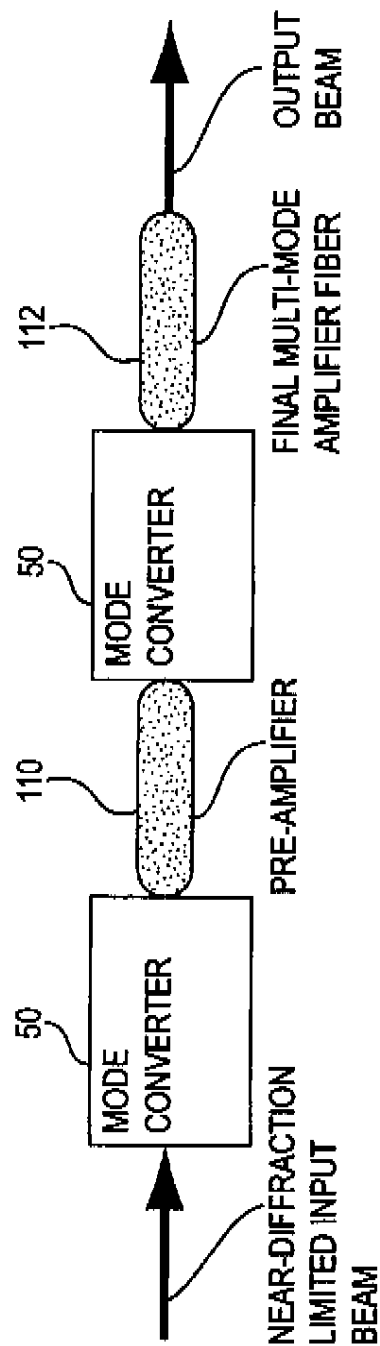


FIG. 11

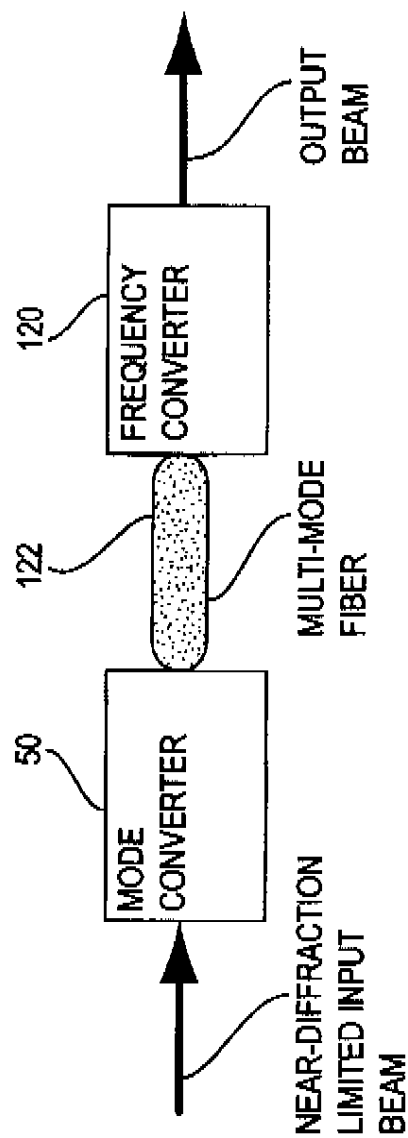


FIG. 12

5,818,630

1

SINGLE-MODE AMPLIFIERS AND COMPRESSORS BASED ON MULTI-MODE FIBERS

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to the use of multi-mode fibers for amplification of laser light in a single-mode amplifier system.

2. Description of the Related Art

Rare-earth-doped optical fibers have long been considered for use as sources of coherent light, as evidenced by U.S. Pat. No. 3,808,549 to Maurer (1974), since their light-guiding properties allow the construction of uniquely simple lasers. However, early work on fiber lasers did not attract considerable attention, because no methods of generating diffraction-limited coherent light were known. Many current applications of lasers benefit greatly from the presence of diffraction-limited light.

Only when it became possible to manufacture single-mode (SM) rare-earth-doped fibers, as reported by Poole et al. in "Fabrication of Low-Loss Optical Fibers Containing Rare-Earth Ions", *Optics Letters*, Vol. 22, pp. 737-738 (1985), did the rare-earth-doped optical fiber technology become viable. In this technique, only the fundamental mode of the optical fiber is guided at the lasing wavelength, thus ensuring diffraction-limited output.

Driven by the needs of optical fiber telecommunications for SM optical fiber amplifiers, nearly all further developments for more than a decade in this area were concentrated on perfecting SM fiber amplifiers. In particular, the motivation for developing SM fiber amplifiers stemmed from the fact that SM fiber amplifiers generate the least amount of noise and they are directly compatible with SM fiber optic transmission lines. SM fiber amplifiers also have the highest optical transmission bandwidths, since, due to the absence of any higher-order modes, modal dispersion is completely eliminated. In general, modal dispersion is the most detrimental effect limiting the transmission bandwidth of multimode (MM) optical fibers, since the higher-order modes, in general, have different propagation constants.

However, in the amplification of short-optical pulses, the use of SM optical fibers is disadvantageous, cause the limited core area limits the saturation energy of the optical fiber and thus the obtainable pulse energy. The saturation energy of a laser amplifier can be expressed as

$$E_{sat} = \frac{h\nu A}{\sigma}$$

where h is Planck's constant, ν is the optical frequency, σ is the stimulated emission cross section and A is the core area. The highest pulse energy generated from a SM optical fiber to date is about 160 μ J (disclosed by Taverner et al. in *Optics Letters*, Vol. 22, pp. 378-380 (1997)), and was obtained from a SM erbium-doped fiber with a core diameter of 15 μ m, which is about the largest core diameter that is compatible with SM propagation at 1.55 μ m. This result was obtained with a fiber numerical aperture of NA=0.07. Any further increase in core diameter requires a further lowering of the NA of the fiber and results in an unacceptably high sensitivity to bend-losses.

As an alternative to SM amplifiers amplification in multimode (MM) optical fibers has been considered. See, for example, "Chirped-pulse amplification of ultrashort pulses with a multimode Tm:ZBLAN fiber upconversion ampli-

2

fier" by Yang et al., *Optics Letters*, Vol. 20, pp. 1044-1046 (1995). However, in general, amplification experiments in MM optical fibers have led to non-diffraction-limited outputs as well as unacceptable pulse broadening due to modal dispersion, since the launch conditions into the MM optical fiber and mode-coupling in the MM fiber were not controlled.

It was recently suggested by Griebner et al. in "Efficient laser operation with nearly diffraction-limited output from a diode-pumped heavily Nd-doped multimode fiber", *Optics Letters*, Vol. 21, pp. 266-268 (1996), that a near diffraction-limited output can be obtained from a MM fiber laser when keeping the fiber length shorter than 15 mm and selectively providing a maximum amount of feedback for the fundamental mode of the optical fiber. In this technique, however, severe mode-coupling was a problem, as the employed MM fibers supported some 10,000 modes. Also, only an air-gap between the endface of the MM fiber and a laser mirror was suggested for mode-selection. Hence, only very poor modal discrimination was obtained, resulting in poor beam quality.

In U.S. Pat. No. 5,187,759 to DiGiovanni et al., it was suggested that amplified spontaneous emission (ASE) in a MM fiber can be reduced by selectively exciting any active ions close to the center of the fiber core or by confining the active ions to the center of the fiber core. Since the overlap of the low-order modes in a MM optical fiber is highest with the active ions close to the center of the fiber core, any ASE will then also be predominantly generated in low-order modes of the MM fiber. As a result, the total amount of ASE can be greatly reduced in MM fiber, since no ASE is generated in high-order modes. However, DiGiovanni described dopant confinement only with respect to ASE reduction. DiGiovanni did not suggest that, in the presence of mode-scattering, dopant confinement can enhance the beam quality of the fundamental mode of the MM fiber under SM excitation. Also, the system of DiGiovanni did not take into account the fact that gain-guiding induced by dopant confinement can in fact effectively guide a fundamental mode in a MM fiber. This further reduces ASE in MM fibers as well as allowing for SM operation.

In fact, the system of DiGiovanni et al. is not very practical, since it considers a MM signal source, which leads to a non-diffraction-limited output beam. Further, only a single cladding was considered for the doped fiber, which is disadvantageous when trying to couple high-power semiconductor lasers into the optical fibers. To couple high-power semiconductor lasers into MM fibers, a double-clad structure, as suggested in the above-mentioned patent to Maurer, can be of an advantage.

To the inventors' knowledge, gain-guiding has not previously been employed in optical fibers. On the other hand, gain-guiding is well known in conventional semiconductor and solid-state lasers. See, for example, "Alexandrite-laser-pumped Cr³⁺:Li₂AlF₆" by Harter et al., *Optics Letters*, Vol. 17, pp. 1512-1514 (1992). Indeed, in SM fibers, gain-guiding is irrelevant due to the strong confinement of the fundamental mode by the waveguide structure. However, in MM optical fibers, the confinement of the fundamental mode by the waveguide structure becomes comparatively weaker, allowing for gain-guiding to set in. As the core size in a MM fiber becomes larger, light propagation in the fiber structure tends to approximate free-space propagation. Thus, gain-guiding can be expected eventually to be significant, provided mode-coupling can be made sufficiently small. In addition to providing high pulse energies, MM optical fiber amplifiers can also be used to amplify very high peak power pulses due to their increased fiber cross section compared to

5,818,630

3

SM fiber amplifiers. MM undoped fibers and MM amplifier fibers can also be used for pulse compression as recently disclosed by Fernann et al. in U.S. application Ser. No. 08/789,995 (filed Jan. 28, 1997). However, this work was limited to the use of MM fibers as soliton Raman compressors in conjunction with a nonlinear spectral filtering action to clean-up the spectral profile, which may limit the overall efficiency of the system.

Compared to pulse compression in SM fibers, such as that disclosed in U.S. Pat. No. 4,913,520 to Kafka et al., higher-pulse energies can be obtained in MM fibers due to the increased mode-size of the fiber. In particular, V-values higher than 2.5 and relatively high index differences between core and cladding (i.e. a $\Delta n > 0.3\%$) can be effectively employed. In "Generation of high-energy 10-fs pulses by a new pulse compression technique", Conference on Lasers and Electro-Optics, CLEO 91, paper DTuR5, Optical Society of America Technical Digest Series, #9, pp. 189-190 (1996), M. Nisoli et al. suggested the use of hollow-core fibers for pulse-compression, as hollow-core fibers allow an increase in the mode size of the fundamental mode. However, hollow-core fibers have an intrinsic transmission loss, they need to be filled with gas, and they need to be kept straight in order to minimize the transmission losses, which makes them highly impractical.

As an alternative to obtaining high-power pulses, chirped pulse amplification with chirped fiber Bragg gratings may be employed, as disclosed in U.S. Pat. No. 5,499,134 to Galvanauskas et al. (1996). One of the limitations of this technique is that, in the compression grating, a SM fiber with a limited core area is employed. Higher pulse energies could be obtained by employing chirped fiber Bragg gratings in MM fibers with reduced mode-coupling for pulse compression. Indeed, unchirped fiber Bragg gratings were recently demonstrated in double-mode fibers by Strasser et al. in "Reflective-mode conversion with UV-induced phase gratings in two-mode fiber", *Optical Society of America Conference on Optical Fiber Communication, OFC97*, pp. 348-349, (1997). However, these gratings were blazed to allow their use as mode-converters, i.e., to couple the fundamental mode to a higher-order mode. The use of Bragg gratings in pulse-compression calls for an unblazed grating to minimize the excitation of any higher-order modes in reflection.

It has long been known that a SM signal can be coupled into a MM fiber structure and preserved for propagation lengths of 100s of meters. See, for example, "Pulse Dispersion for Single-Mode Operation of Multimode Cladded Optical Fibers", Gambling et al., *Electron. Lett.*, Vol. 10, pp. 148-149, (1974) and "Mode conversion coefficients in optical fibers", Gambling et al., *Applied Optics*, Vol. 14, pp. 1538-1542, (1975). However, Gambling et al. found low levels of mode-coupling only in liquid-core fibers. On the other hand, mode-coupling in MM solid-core fibers was found to be severe, allowing for the propagation of a fundamental mode only in mm lengths of fiber. Indeed, as with the work by Griebner et al., Gambling et al. used MM solid-core optical fibers that supported around 10,000 or more modes.

In related work, Gloge disclosed in "Optical Power Flow in Multimode Fibers", *The Bell System Technical Journal*, Vol. 51, pp. 1767-1783, (1972), the use of MM fibers that supported only 700 modes, where mode-coupling was sufficiently reduced to allow SM propagation over fiber lengths of 10 cm.

However, it was not shown by Gloge that mode-coupling can be reduced by operating MM fibers at long wavelengths

4

(1.55 μm) and by reducing the total number of modes to less than 700. Also, in this work, the use of MM fibers as amplifiers and the use of the nonlinear properties of MM fibers was not considered.

The inventors are not aware of any prior art using MM fibers to amplify SM signals where the output remains primarily in the fundamental mode, the primary reason being that amplification in MM fibers is typically not suitable for long-distance signal propagation as employed in the optical telecommunication area. The inventors are also not aware of any prior art related to pulse compression in multi-mode fibers, where the output remains in the fundamental mode.

All of the above-mentioned articles, patents and patent applications are hereby incorporated herein by reference.

SUMMARY OF THE INVENTION

It is an object of the present invention to increase the energy storage potential in an optical fiber amplifier and to produce peak powers and pulse energies which are higher than those achievable in single-mode (SM) fibers before the onset of undesirable nonlinearities and gain saturation.

Another object of the present invention is to achieve amplification of the fundamental mode within a multi-mode (MM) fiber while reducing amplified spontaneous emission (ASE).

A further object of the present invention is to employ gain-guiding within a MM fiber to improve the stability of the fundamental mode.

Yet another object of the present invention is to compress high peak power pulses into the range of a few psec to a fsec while preserving a near diffraction-limited output.

To achieve the above objects, the present invention employs a multimode (MM) optical fiber in an optical amplification system. According to the present invention, MM optical fibers, i.e., fibers with a V-value greater than approximately 2.5, provide an output in the fundamental mode. This allows the generation of much higher peak powers and pulse energies compared to SM fibers before the onset of undesirable nonlinearities and gain saturation. The increased fiber cross section equally greatly increases the energy storage potential in an optical fiber amplifier. The amplification system of the present invention is useful in applications requiring ultrafast and high-power pulse sources.

According to one aspect of the present invention, the gain medium is in the center of the MM fiber so that the fundamental mode is preferentially amplified and spontaneous emission is reduced. Further, gain-confinement is used to stabilize the fundamental mode in a fiber with a large cross section by gain guiding.

According to one embodiment of the present invention, the exploitation of self-phase modulation and other nonlinearities in (rare-earth) doped or undoped MM fibers allows the compression of high peak power pulses into the range of a few fsec while a near diffraction-limited output is preserved.

According to another embodiment of the present invention, by writing chirped fiber Bragg gratings into MM optical fibers with reduced mode-coupling, the power limits for linear pulse compression of high-power optical pulses are greatly increased. Further, by employing double-clad MM fiber amplifiers, pumping with relatively large-area high-power semiconductor lasers is made possible.

According to yet another embodiment of the present invention, the incorporation of efficient mode-filters enables

5,818,630

5

cw lasing in a near diffraction-limited single mode from (rare-earth) doped MM optical fibers.

According to yet another embodiment of the present invention, MM optical fibers allow the construction of fiber optic regenerative amplifiers and high-power Q-switched lasers. Further, MM optical fibers allow the design of cladding-pumped fiber lasers using dopants with relatively weak absorption cross sections.

These and other objects and features of the present invention will be apparent from the following detailed description of the preferred embodiments and the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a diagrammatic view of a multi-mode fiber amplifier system according to the first embodiment of the present invention.

FIG. 2 is a graph showing the coupling efficiency of a multi-mode amplifier fiber into a mode-filter fiber as a function of bend-radius of the multi-mode amplifier fiber.

FIG. 3 is a graph showing the autocorrelation of the amplified pulses from a multi-mode amplifier fiber measured under optimum mode-match conditions.

FIG. 4 is a graph showing the autocorrelation of the amplified pulses from a multi-mode amplifier fiber measured under non-optimum mode-match conditions.

FIG. 5 is a block diagram of a multi-mode fiber amplifier system according to the second embodiment of the present invention.

FIG. 6 is a block diagram of a multi-mode fiber amplifier system according to the third embodiment of the present invention, wherein a pulse compressor is disposed at an output of the multi-mode fiber.

FIG. 7 is a diagrammatic view of a multi-mode fiber amplifier system according to a fourth embodiment of the present invention.

FIG. 8 is a conceptual drawing of a fiber cross section employing a doped multi-mode fiber core and an undoped fiber cladding according to a fifth embodiment of the present invention.

FIG. 9 is a diagrammatic view of a multi-mode fiber amplifier system according to a sixth embodiment of the present invention, wherein a fiber regenerative amplifier is constructed from a multi-mode fiber amplifier.

FIG. 10 is a diagrammatic view of a multi-mode fiber amplifier system according to a seventh embodiment of the present invention, wherein a MM Q-switched fiber laser source is constructed.

FIG. 11 is a block diagram of a multi-mode fiber amplifier system according to the eighth embodiment of the present invention, wherein a preamplifier is inserted before the multi-mode fiber.

FIG. 12 is a block diagram of a multi-mode fiber amplifier system according to the ninth embodiment of the present invention, wherein a frequency converter is disposed at an output of the multi-mode fiber.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 illustrates an amplifier system according to a first embodiment of the present invention. In the example shown in FIG. 1, a femtosecond single-mode (SM) fiber oscillator 10, such as an erbium fiber oscillator, is coupled into a multi-mode (MM) fiber amplifier 12, such as an erbium/

6

ytterbium fiber amplifier. Other examples of suitable MM fiber amplifiers include those doped with Er, Yb, Nd, Tm, Pr or Ho ions. Oscillators suitable for use in this system are described in the above-mentioned U.S. patent application Ser. No. 08/789,995 to Fermann et al.

A two-lens telescope 14 (L1 and L2) is used to match the mode from the oscillator 10 to the fundamental mode of the MM amplifier 12. In addition, the output of the pumped MM fiber 12 is imaged into a second SM fiber (mode-filter (MF) fiber 16 in FIG. 1) using lenses L3 and L4. Lenses L3 and L5 and beamsplitter 18 are used to couple the pump light from pump source 20 into the amplifier fiber, as described below.

In one example of the system arranged according to FIG. 1, the oscillator 10 delivers 300 fsec near bandwidth-limited pulses at a repetition rate of 100 MHz at a wavelength of 1.56 μm with a power level of 14 mW.

The amplifier fiber 12 can be, for example, a double-clad MM erbium/ytterbium amplifier with a core diameter of $\sim 28 \mu\text{m}$ and a core numerical aperture of NA=0.19. The inner cladding in this example has a diameter of $\sim 220 \mu\text{m}$ and a numerical aperture of NA=0.24. The core is located in the center of the inner cladding. The length of the amplifier is 1.10 m.

To increase the number of propagating modes in the MM amplifier 12 and for testing purposes, shorter wavelengths such as 780 and 633 nm were also used. In this, a femtosecond laser source operating at 780 nm and a cw laser source at 633 nm can be launched into the MM amplifier fiber 12. The MF fiber 16 can then be replaced with a fiber with a core diameter of 4 μm to ensure SM operation at these two wavelengths.

The approximate number of modes in the MM amplifier is calculated from its V-value.

$$V = \frac{2\pi a}{\lambda} \text{NA}, \quad \text{number of modes} = \frac{1}{2} V^2 \quad (1)$$

where a is the core radius and λ is the signal wavelength. The V-value at 1.55 μm is thus $V \sim 10.8$, and the number of modes is hence calculated as ~ 58 for the above example. Typically, a fiber is considered MM when the V-value exceeds 2.41, i.e., when modes in addition to the fundamental mode can propagate in the optical fiber.

For equal excitation of N modes of a MM fiber supporting N modes the maximum coupling efficiency into a SM fiber is given approximately by

$$\eta = (\theta_0/\theta_{\text{max}})^2 \sim 1/N, \quad (2)$$

where $\theta_0 = \lambda/4a$ is the divergence half-angle of the fundamental mode of the MM fiber. θ_{max} is the maximum divergence half-angle of the outer-most modes of the MM fiber. It is assumed that the output from the MM fiber is linearly polarized which is an appropriate assumption for the excitation of the lowest order modes in the fiber. Under SM excitation of the MM fiber and in the absence of mode-coupling, $\theta_{\text{max}}(z) = \theta_0$ independent of fiber length. However, in the presence of mode-coupling θ_{max} will increase, and, as a result, the possible coupling efficiency from the output of the MM fiber into a SM fiber will decrease as $\eta(z) = (\theta_0/\theta_{\text{max}}(z))^2$. Using the above-mentioned work by Gloge, $\eta(z)$ can be written as:

$$\eta(z) = \frac{\theta_0^2}{4Dz + \theta_0^2} \quad (3)$$

where D is the mode-coupling coefficient as defined by Gloge. Thus, a measurement of $\eta(z)$ gives the mode-

5,818,630

7

coupling coefficient D . Equally, from equation (2), a measurement of η gives the approximate number of excited modes of a MM fiber. It is instructive to relate N to the M^2 -value that is typically used to characterize the quality of near-diffraction-limited optical beams. It may be shown that $N \approx \sqrt{M^2}$. According to the present invention, a low level of mode-coupling is desirable, so that the amplified beam provided at the output of the MM fiber amplifier 12 is substantially in the fundamental mode. Accordingly, an M^2 -value less than 10 is desirable, with an M^2 -value less than 4 being preferable, and an M^2 -value less than 2 being more preferable. Further, the number of modes is preferably in the range of 3 to 3000 and more preferably in the range of 3 to 1000.

Mode-coupling was measured in a 1.1 m length of unpumped amplifier fiber for the above-described erbium/ytterbium fiber (fiber 1), and three commercially available MM-fibers (fiber 2, 3 and 4). The fiber parameters and the mode-coupling coefficient D (in m^{-1}) of these fibers are shown in Table 1. Fibers 1, 3 and 4 are made by the MCVD process; fiber 2 is made by a rod-in-tube technique.

TABLE 1

	fiber 1	fiber 2	fiber 3	fiber 4
NA	0.19	0.36	0.13	0.13
core diameter (μm)	28	50	50	50
cladding diameter (μm)	200	125	125	250
number of modes at 1.55 μm	58	665	87	87
number of modes at 0.79 μm	223			
number of modes at 0.63 μm	350			
$D(m^{-1})$ at 1.55 μm	$< 2 \times 10^{-9}$	8×10^{-4}	8×10^{-3}	7×10^{-9}
$D(m^{-1})$ at 0.79 μm	4×10^{-6}			
$D(m^{-1})$ at 0.63 μm	2×10^{-5}			
$L_b(mm)$ at 1.55 μm	1.9	5.3	5.7	5.7
$L_b(mm)$ at 0.79 μm	3.3			
$L_b(mm)$ at 0.63 μm	4.1			
$M^2(1\ m)$ at 1.55 μm	1.0	200	5.4	1.25
$M^2(1\ m)$ at 0.79 μm	1.2			
$M^2(1\ m)$ at 0.63 μm	2.6			

The coupling coefficients allow, in turn, the calculation of the expected M^2 value. In this example, the calculated M^2 -values were produced after propagation through 1 m of MM fiber 12. For fiber 1, a good agreement between the calculated and separately measured M^2 -values was obtained.

The beat length L_b between the fundamental LP_{01} and the next higher-order LP_{11} mode is also given in Table 1. The beat length L_b is defined as the length it takes for the two modes to accumulate a differential phase-shift of 2π along the propagation direction. Assuming a constant scattering power spectrum, for a fixed wavelength, D can be shown to be proportional to L_b^{-4} .

See: D. Marcuse, "The Theory of Dielectric Optical Waveguides", p. 238, Academic Press (1974); Gloge. The longer the beat length, the closer the modes are to being phase-matched and the more power will couple as a function of length. Since, as disclosed by Gloge, mode-coupling is expected to be largest between adjacent modes, it is desirable to use LP_{01}/LP_{11} beat lengths as short as possible to avoid mode-coupling.

In general, high levels of mode-coupling can be expected from fibers with high scattering loss. This suggests the possibility of low mode-coupling coefficients at long wavelengths in fibers with low scattering loss. As can be seen from Table 1, a dramatic reduction of mode-coupling occurs with increased wavelength in fiber 1. An acceptable level of

8

mode-coupling is achieved in fiber 1 down to wavelengths as short as 790 nm. Since the number of modes of an optical fiber depends only on the ratio a/λ , a fiber similar to fiber 1 with a core diameter as large as 56 μm can produce acceptable levels of mode-coupling in a 1 m length. Due to the reduction of scattering at longer wavelengths, even larger core diameters are acceptable at longer wavelengths. For example, a MM fiber with a core diameter of 60 μm can amplify pulses with a peak power 16 times larger than possible with SM amplifiers described by Taverner et al. Indeed, acceptable levels of mode coupling were obtained for a specifically designed fiber with a 50 μm core diameter as evident from Table 1 and explained in the following.

Further, it is clear that, to minimize mode-coupling, step-index MM fibers are more useful than graded-index MM fibers, since the propagation constants in graded-index fibers are very similar, which greatly increases their sensitivity to mode coupling. To minimize mode-coupling, the difference in the propagation constants between fiber modes is preferably maximized.

Fiber 2 was manufactured by a rod-in-tube technique with intrinsic high scattering losses leading to much larger mode-coupling coefficients compared to the MCVD-grown fibers 1, 3 and 4. Also, the mode-coupling coefficients measured in fiber 2 are similar to results obtained by Gambling et al. and Griebner et al., who also used step-index solid-core fibers manufactured by rod-in-tube techniques. As a consequence, reduced mode-coupling can be expected from directly grown MM fibers employing, for example, MCVD, OVD, PCVD or VAD fiber fabrication techniques.

As shown in Table 1, the mode-coupling coefficients obtained in fiber 4 at 1.55 μm are about a factor of 11 smaller than in fiber 3. This difference is explained by the fact that the outside diameter of fiber 4 is 250 μm , whereas the outside diameter of fiber 3 is 125 μm . In general, a thicker fiber is stiffer and less sensitive to bend and micro-bend induced mode-coupling, as evident from Table 1.

In experiments conducted by the inventors, the lowest mode-coupling coefficients were obtained by longitudinally stretching the optical fibers. For example, the mode-scattering coefficients of fiber 2 and 3 were measured while keeping the fiber under tension and while keeping the fiber straight. The application of tension in short lengths of fibers can be useful in obtaining the best possible mode-quality.

Mode-coupling was also measured in a configuration where the amplifier fiber (fiber 1) was pumped, as shown in FIG. 1. Specifically, the amplifier was pumped at a wavelength of 980 nm contra-directionally with respect to the signal with a launched power up to 3 W from a broad-stripe semiconductor laser with an active area of $1 \times 500\ \mu m$, where demagnification was employed to optimize the power coupling into the inner cladding of the MM amplifier fiber. The amplifier was cleaved at an angle of about 8° to eliminate spurious feedback. A signal power up to 100 mW was then extracted from the amplifier system at 1.56 μm .

The coupling efficiency of the MM amplifier fiber 12 into the MF fiber 16 as a function of bend-radius of the MM amplifier fiber 12 is shown in FIG. 2. For a straight MM amplifier fiber and for a bend-radius of 10 cm, a coupling efficiency up to 94% is obtained into the MF fiber 16, demonstrating that mode-coupling is nearly completely absent in the MM amplifier fiber 12 and that a SM can indeed propagate over lengths of several meters in such fibers. No clear onset of mode-coupling is visible even for a bend-radius of 5 cm, since, even in this case, a coupling efficiency of about 90% from the MM amplifier fiber 12 to the MF fiber 16 is obtained.

Since the measured coupling efficiencies from the MM amplifier 12 to a SM fiber are nearly the same under

5,818,630

9

unpumped and pumped conditions, it is evident that gain-guiding is relatively weak in this particular amplifier fiber. This observation was also verified by a simple computer model (see below). However, clearly any dopant confinement in the center of the MM amplifier core will predominantly lead to amplification of the fundamental mode. Any light scattered into higher-order modes will experience less gain and, due to the reduced intensity overlap of the higher-order modes with the fundamental mode, low levels of scattered light in higher-order modes will also not saturate the gain of the fundamental mode. Thus, while in the above-described experimental example, the mode-scattering coefficients were so low that any effects due to gain-guiding were not readily observable, in general, gain-guiding plays a role in a MM amplifier system according to the present invention. In addition, the above-mentioned computer model predicts the onset of gain-guiding of the fundamental mode in MM fibers with larger core diameter and/or reduced refractive index differences between the core and cladding.

As the mode diameter increases, the size of the SM can be determined by the gain profile under small signal conditions, i.e. in the absence of gain saturation. This allows a length-dependent mode size. Initially, under small signal conditions, the mode is confined by gain-guiding. As the gain saturates, gain guiding becomes less relevant and the mode size can increase, limited eventually by the core of the MM fiber. A length-dependent mode size can also be achieved by employing a core size which tapers along the fiber length. This can, for example, be achieved by tapering the outside fiber diameter along the fiber length.

In the presence of gain-guiding, amplified spontaneous emission (ASE) is reduced, as the MM fiber essentially becomes SM. In the presence of gain-guiding, ASE is also guided predominantly in the fundamental mode, rather than in all possible modes of the MM fiber, leading to an improvement in the noise properties of the MM fiber.

Equally, in the experimental example, dopant-confinement was observed to lead to a significant reduction in the amplified spontaneous emission (ASE) levels in the fiber. This was verified by measuring the coupling efficiency of the ASE from the MM amplifier 12 into the MF fiber 16. In this case, no signal light was coupled into the MM amplifier fiber 12. For an ASE power level of 1 mW, a coupling efficiency as high as 15% was measured. A comparison with equation (2) indicates that ASE is generated mainly in about 13 low-order modes (here a factor of two from polarization degeneracy is accounted for), i.e., ASE is generated in only about 20% of the total mode-volume of the amplifier fiber. The large reduction in ASE which was observed not only reduces the noise level in the amplifier; low levels of ASE also allow a reduction of the signal power that is required to saturate the amplifier. To extract the highest energy from an oscillator-amplifier signal pulse source, an operation of the amplifier in saturation is generally preferred.

The coupling efficiency at 1.55 μm and at 780 nm from the MM amplifier fiber 12 to the MF fiber 16 was not found to vary when applying small mechanical perturbations to the optical fiber. In a practical optical system, the applied mechanical perturbations are small compared to the perturbations inflicted by a 5 cm bend radius, which indicates that long-term stability of the mode-propagation pattern in such fibers can be achieved.

The MM amplifier 12 is polarization preserving for bend-radii as small as 10 cm. To obtain a high-degree of polarization holding, elliptical fiber cores or thermal stresses can be used in such fibers.

10

The autocorrelation of the amplified pulses from the MM amplifier fiber 12 (bend radius=10 cm) measured under the condition of optimum mode-match and a condition of non-optimum mode-match are respectively shown in FIGS. 3 and 4. Under non-optimum mode-match, the autocorrelation displays several peaks due to the excitation of higher-order modes, which have different propagation constants. However, under optimum mode-matching conditions, any secondary peaks are suppressed to better than 1%, which indicates the high-quality of the pulses emerging from the MM amplifier fiber.

In general, the spectrum of the pulses measured at the output of the MM amplifier fiber 12 is more critically dependent on the coupling conditions than the autocorrelation. The reason for this is that the spectral measurement is sensitive to the phase between the fundamental mode and the higher-order modes, i.e., an energy content of higher-order modes of only 1% in the output of the MM fiber leads to a perturbation of the shape of the spectrum by 10%.

FIG. 5 is a block diagram of a multi-mode fiber amplifier system according to a second embodiment of the present invention. The system includes a near-diffraction limited input beam, a mode-converter 50 and a MM fiber amplifier 52. The near-diffraction limited input beam can be generated from any laser system, which need not be a fiber laser. The near-diffraction limited input beam can contain cw or pulsed radiation. The mode-converter 50 can consist of any type of optical imaging system capable of matching the mode of the MM amplifier 52. For example, a lens system may be employed. Alternatively, a section of tapered fiber may be employed, such that the output mode at the end of the tapered fiber is matched to the mode of the MM amplifier fiber 52. In this case, the mode-converter can be spliced directly to the MM fiber 52 producing a very compact set-up. Any pumping configuration could be employed for the MM amplifier fiber, such as contra- or co-directional pumping with respect to the signal or side-pumping. Equally, the NA of the pump light could be reduced to minimize ASE. In this case, the use of just a single-clad fiber is more advantageous, where the pump light is directed into the fiber core. In general, the MM amplifier 52 can have a single, double or multiple cladding.

In the case of co-directional pumping, the pump light and the signal light are launched via a dichroic beamsplitter (not shown). The coupling optics are then optimized to simultaneously optimize the coupling of the pump beam and the signal beam.

A single or a double pass of the signal through the MM fiber 52 is most convenient. In the case of a double-pass configuration, a Faraday rotator mirror can be employed to eliminate polarization drifts in the system. Of course, in a double-pass configuration, after the first pass through the amplifier the coupling of the signal into higher-order modes must be avoided to ensure a near-diffraction limited output.

Optionally, linear or nonlinear optical elements can be used at the output of the system. Such a system is compatible with any application that has been used in conjunction with conventional laser systems.

Many nonlinear applications indeed require high peak pulse powers for their efficient operation, which are very difficult to achieve in cladding-pumping SM amplifiers due to the 10s of meters of fiber length that are typically employed in such systems. Even in standard SM optical amplifiers, peak powers greater than 1 kW/amplifier length can rarely be achieved. In contrast, peak powers of ~ 15 kW are achievable in a 1.5 m length of double-clad Er/Yb fiber (fiber 1 from Table 1) without appreciable non-linear effects, i.e., peak powers greater than 20 kW/amplifier length can be achieved.

5,818,630

11

According to the present invention, the use of a MM amplifier is beneficial not only by way of allowing the use of a large core diameter; the use of a MM amplifier also allows a reduction of the ratio cladding/doped core diameter, which minimizes the amplifier length and thus the amplifier non-linearity. However, this leads to the generation of more ASE noise.

FIG. 6 is a block diagram illustrating a multi-mode fiber amplifier system according to a third embodiment of the present invention. In the system of the third embodiment, high-power optical pulses can be propagated (or amplified) in undoped (or amplifier) MM fibers, such that spectral broadening is obtained to allow for pulse compression of the amplifier output. For applications in nonlinear pulse-compression, optical fibers with either positive (non-soliton-supporting) or negative (soliton-supporting) dispersion can be employed. The power levels in the multi-mode fiber 60 are raised to obtain an appreciable amount of self-phase modulation. The interplay of dispersion and self-phase modulation in the optical fiber can then be used to broaden the spectrum of the optical pulses and to obtain pulse compression.

When the MM fiber 60 is soliton supporting, higher-order soliton compression may be used to produce short pulses from the MM fiber 60 directly. In general, in the case of positive dispersion (non-soliton supporting) fiber, additional linear or nonlinear pulse-compression components must be used to compress the spectrally broadened optical pulses. In this case, a conventional linear pulse compressor 62 (such as a prism, grating, grism or SM chirped fiber Bragg grating) may be used at the output of the system. Also, chirped periodically poled doubling crystals may be used to obtain a compressed, frequency-doubled pulse. Equally, chirped fiber Bragg gratings may be written into the MM optical fiber 60 with reduced mode-coupling to reduce the nonlinearities of such structures when applied to linear pulse compressor 62. The Bragg grating should not be blazed to eliminate the excitation of higher-order modes in reflection.

FIG. 7 is a diagrammatic view of a system according to a fourth embodiment of the present invention. As shown in FIG. 7, a mode-filter 70 is inserted in front of one of the cavity mirrors M1 and M2 to ensure a diffraction-limited output of the system. The mode filter 70 can consist of a standard SM fiber in conjunction with appropriate mode-matching optics. Alternatively, a tapered fiber can be used (as discussed above) to provide for mode-matching. For optimum mode-coupling the efficiency of the laser will be nearly as high as for an all-SM laser. However, the use of MM amplifier 76 allows for increased design flexibility. Thus, double-clad erbium/ytterbium fibers with different core-cladding ratios can be employed wherever appropriate.

According to a fifth embodiment, the use of MM fiber allows the design of double-clad fibers with low absorption cross sections. For example, a double-clad Er-doped amplifier fiber may be constructed from MM fibers. Typically Er-doped double-clad fibers are relatively inefficient, since large cladding/core ratios have to be employed in order to absorb pump light from broad area diode lasers while still preserving a SM fiber core. Typically, such a design would involve a $\Phi_{cl} = 100 \mu\text{m}$ diameter cladding and a $\Phi_{co} = 10 \mu\text{m}$ diameter core. The effective absorption of such a structure is 100 times $(=\Phi_{cl}/\Phi_{co})^2$ smaller than the absorption in a single-clad Er-doped fiber. Thus, 100 times longer fiber amplifier lengths are required in this case. However, by implementing MM Er-doped fiber, the core size can be greatly increased, producing much smaller cladding/core ratios and shorter amplifier lengths which is very beneficial

12

for the design of high-power lasers. Of course, for the design of high-power Er double-clad lasers, cladding diameters even larger than $100 \mu\text{m}$ can be implemented. A conceptual drawing of a fiber cross section employing a doped MM fiber core and an undoped fiber cladding is shown in FIG. 8. As shown in FIG. 8, the active dopant is confined in a cross section, defined by the dopant profile, substantially smaller than the fiber core, as defined by the refractive index profile. Of course, in such laser system, dopant confinement increases the amplifier length, thus only relatively weak doping confinement is useful.

According to a sixth embodiment of the present invention, as shown in FIG. 9, a fiber regenerative amplifier may be constructed from a MM fiber amplifier 90. A regenerative amplifier is useful for obtaining mJ energies from MM fiber amplifiers. Due to the limited gain of MM fiber amplifiers, the extraction of mJ energies will typically require several passes through the amplifier, which is facilitated by the regenerative amplifier. As shown in FIG. 9, a fast optical switch (OS) 92 is used to switch the pulses in and out of the regenerative amplifier. A mode-filter 94 can also be included to "clean-up" the fiber mode in the amplification process. The mode-filter 94 can consist of a spatial filter to minimize any nonlinearities in the regenerative amplifier.

The seed pulse is selected from the oscillator 96 by the optical switch 92 at the desired repetition rate. The Faraday rotator 98 and the polarization beam splitter 99 are used to couple the amplified pulse out of the system.

Either cw or pulsed pumping of the amplifier can be employed.

According to a seventh embodiment of the present invention shown in FIG. 10, a MM Q-switched fiber laser source is constructed. The large cross-sections possible with MM fibers allow greatly increasing the energy storage compared to a single-mode fiber. As a result, high-power Q-switched pulses may be directly generated from such a system. Typically, these pulses have a duration in the nsec regime. As shown in FIG. 10, a mode-filter 100 can also be included to ensure an optimum mode-quality. The optical switch 102 is employed for output coupling and it also serves to modulate the loss (Q) of the cavity defined by the two mirrors M1 and M2 and the MM amplifier 104. Alternatively, the output can be extracted by using a partially transmissive mirror M2.

According to an eighth embodiment of the present invention shown in FIG. 11, a preamplifier is included in front of the final MM amplifier fiber 112 to fully saturate the MM amplifier fiber 112 and to reduce the level of ASE in the MM amplifier fiber 112. The preamplifier can be SM and also MM, where it is useful to select the core radius of the preamplifier fiber 110 to be smaller than the core radius of the final MM amplifier fiber 112 to minimize the growth of ASE. One isolator (not shown) can be inserted between the laser source and the preamplifier and another isolator (not shown) can be inserted between the preamplifier 110 and the final MM amplifier fiber 112 further to reduce ASE. Similarly, narrow band optical filters (not shown) can be included anywhere in the system to reduce ASE. Also, optical switches (not shown) can be used in between the laser source, the preamplifier 110 and the final amplifier 112 to reduce the amount of ASE.

More than one preamplifier can be used in the system, where isolators and optical filters and optical switches can be used to minimize the amount of generated ASE in the system. Further, nonlinear processes in the preamplifiers and the final MM amplifier can be used for pulse compression.

According to a ninth embodiment of the present invention shown in FIG. 12, a frequency converter 120 is included

5,818,630

13

downstream of the MM amplifier fiber 122 to frequency convert the output amplified beam. The frequency converter can be a non-linear crystal, such as a periodically-poled or aperiodically poled LiNbO₃ crystal which frequency doubles the output beam.

Although several exemplary embodiments have been herein shown and described, those of skill in the art will recognize that many modifications and variations are possible without departing from the spirit and scope of the invention, and it is intended to measure the invention only by the appended claims.

What is claimed is:

1. An optical amplification system, comprising:

a laser source generating an input beam having a nearly diffraction limited mode;

a multi-mode fiber amplifier;

a mode converter receiving the input beam and converting the mode of the input beam to match a fundamental mode of the multi-mode fiber amplifier, and providing a mode-converted input beam to said multi-mode fiber amplifier; and

a pump source coupled to said multi-mode fiber amplifier, said pump optically pumping said multi-mode fiber amplifier, said multi-mode fiber amplifier providing at an output thereof an amplified beam substantially in the fundamental mode.

2. The optical amplification system according to claim 1, wherein the fundamental mode is substantially guided by gain-guiding.

3. The optical amplification system according to claim 2, wherein inter-modal scattering from the fundamental mode to any higher-order mode is substantially reduced by gain-guiding of the fundamental mode.

4. The optical amplification system according to claim 2, wherein, as a result of substantial gain-guiding, the size of the fundamental mode in said multi-mode fiber amplifier varies along the fiber length.

5. The optical amplification system according to claim 1, wherein said multi-mode fiber amplifier comprises a fiber core, and wherein a dopant is confined in an area in a central section of the fiber core substantially smaller than a total fiber core area.

6. The optical amplification system according to claim 1, wherein said multi-mode fiber amplifier comprises a fiber core, and wherein a dopant is confined in an area in a central section of the fiber core substantially smaller than a total fiber core area, and wherein mode-coupling into higher-order modes is reduced by gain-guiding.

7. The optical amplification system according to claim 1, wherein a gain of the fundamental mode is substantially higher than a gain of any other mode present in said multi-mode fiber amplifier.

8. The optical amplification system according to claim 1, wherein a size of the fundamental mode in said multi-mode fiber amplifier varies along length of said multi-mode fiber amplifier in accordance with a change in fiber diameter along the length of said multi-mode fiber.

9. The optical amplification system according to claim 1, wherein a size of the fundamental mode in said multi-mode fiber amplifier varies along a length of said multi-mode fiber amplifier in accordance with a change in a core or doped core diameter along the length of said multi-mode fiber.

10. The optical amplification system according to claim 1, wherein said multi-mode fiber amplifier is doped with rare-earth-ions.

11. The optical amplification system according to claim 1, wherein said multi-mode fiber amplifier is doped with at least one of: Er, Er/Yb, Yb, Nd, Tm, Pr, Ho ions.

14

12. The optical amplification system according to claim 1, wherein said multi-mode fiber amplifier comprises a double cladding structure.

13. The optical amplification system according to claim 1, wherein said multi-mode fiber amplifier is polarization maintaining.

14. The optical amplification system according to claim 1, wherein the amplified beam passes through said multi-mode fiber amplifier at least twice.

15. The optical amplification system according to claim 1, wherein the mode-converted input beam comprises optical pulses, wherein nonlinear effects within said multi-mode fiber amplifier broaden a spectrum of the optical pulses.

16. The optical amplification system according to claim 1, wherein the mode-converted input beam comprises optical pulses, the system further comprising a compressor which compresses the optical pulses output from said multi-mode fiber amplifier.

17. The optical amplification system according to claim 1, wherein said mode converter comprises a bulk-optics imaging system.

18. The optical amplification system according to claim 1, wherein said mode converter comprises a tapered single-mode fiber.

19. The optical amplification system according to claim 1, wherein said mode converter comprises a combination of a bulk-optics imaging system and a tapered fiber.

20. The optical amplification system according to claim 1, further comprising:

reflectors disposed to form a laser cavity, said reflectors reflecting energy of the amplified beam along an axis; and

means for coupling the reflected energy of the amplified beam out of the laser cavity.

21. The optical amplification system according to claim 20, wherein said reflectors comprise at least one of: a mirror; a fiber Bragg grating; and a bulk grating.

22. The optical amplification system according to claim 20, further comprising an optical switch disposed within the laser cavity, said optical switch enabling Q-switching of the laser cavity.

23. The optical amplification system according to claim 20, further comprising an optical switch disposed within the laser cavity, said optical switch enabling operation of the laser cavity as a regenerative amplifier.

24. The optical amplification system according to claim 1, further comprising a mode filter receiving the amplified beam and providing a mode-filtered beam.

25. The optical amplification system according to claim 24, wherein said mode filter is a single mode fiber.

26. The optical amplification system according to claim 24, wherein said mode filter is a spatial filter.

27. The optical amplification system according to claim 1, wherein a number of propagating modes within said multi-mode fiber amplifier is between 3 and 3000.

28. The optical amplification system according to claim 1, wherein a number of propagating modes within said multi-mode fiber amplifier is between 3 and 1000.

29. The optical amplification system according to claim 1, wherein a wavelength of the amplified beam is greater than 1.100 μm .

30. The optical amplification system according to claim 1, wherein said multi-mode fiber is disposed along a straight line and tension is applied along a longitudinal direction of said multi-mode fiber amplifier.

31. The optical amplification system according to claim 1, wherein said multi-mode fiber has a step-index refractive index profile.

5,818,630

15

32. The optical amplification system according to claim 1, wherein said multi-mode fiber amplifier is manufactured by one of: MCVD, OVD, VAD and PCVD fabrication techniques.

33. The optical amplification system according to claim 1, wherein a number of propagating modes within said multi-mode fiber amplifier is higher than 4, and wherein a fiber Bragg grating is written into said multi-mode fiber amplifier.

34. The optical amplification system according to claim 1, wherein a chirped fiber Bragg grating is written into said multi-mode fiber amplifier.

35. The optical amplification system according to claim 1, wherein said laser source comprises a single-mode fiber oscillator.

36. The optical amplification system according to claim 1, wherein at least one pre-amplifier is inserted between said laser source and said multimode fiber amplifier.

37. The optical amplification system according to claim 36, wherein said at least one pre-amplifier is a second multi-mode amplifier fiber, and wherein a single mode is launched into said multi-mode amplifier fiber.

38. The optical amplification system according to claim 36, wherein said at least one pre-amplifier is a single-mode amplifier fiber.

39. The optical amplification system according to claim 1, wherein said multi-mode fiber amplifier generates pulses with a peak power greater than 1 kW.

40. The optical amplification system according to claim 1, wherein said multi-mode fiber amplifier generates a peak power greater than a ratio of 1 kW/amplifier length.

16

41. The optical amplification system according to claim 1, wherein optical pulses having a width shorter than 10 nsec are amplified in said multi-mode fiber.

42. The optical amplification system according to claim 1, further comprising a nonlinear optical element disposed downstream of said multi-mode fiber amplifier, wherein said amplified beam is frequency converted by said nonlinear optical element.

43. The optical amplification system according to claim 1, further comprising a nonlinear crystal disposed downstream of said multi-mode fiber amplifier, wherein said amplified beam is frequency doubled in said nonlinear crystal.

44. The optical amplification system according to claim 43, wherein said nonlinear crystal comprises a periodically-poled LiNbO₃ crystal.

45. The optical amplification system according to claim 43, wherein said nonlinear crystal comprises an aperiodically-poled LiNbO₃ crystal.

46. The optical amplification system according to claim 1, wherein an M²-value of said multi-mode fiber amplifier is less than 10.

47. The optical amplification system according to claim 1, wherein an M²-value of said multi-mode fiber amplifier is less than 4.

48. The optical amplification system according to claim 1, wherein an M²-value of said multi-mode fiber amplifier is less than 2.

49. The optical amplification system according to claim 1, wherein said multi-mode fiber amplifier comprises a cladding with an outside diameter greater than 125 μ m.

* * * * *

CIVIL COVER SHEET

County in which this action arose Washtenaw

This form, approved by the Judicial Conference of the United States in September 1974, is required for the use of the Clerk of Court for the purpose of filing civil cover sheet. (SEE INSTRUCTIONS ON THE REVERSE OF THE FORM.)

PLAINTIFFS

IMRA AMERICA, INC., a Michigan corporation

(b) County of Residence of First Listed Plaintiff Washtenaw
(EXCEPT IN U.S. PLAINTIFF CASES)

(c) Attorney's (Firm Name, Address, and Telephone Number)

Edward H. Pappas, Robert L. Kelly, J. Benjamin Dolan, Dickinson Wright PLLC
38525 Woodward Avenue, Suite 2000, Bloomfield Hills, MI 48304 (248) 433-7200

DEFENDANTS

IPG PHOTONICS CORPORATION, a Delaware corporation

County of Residence of First Listed Defendant Worcester
(IN U.S. PLAINTIFF CASES ONLY)

NOTE: IN LAND CONDEMNATION CASES, USE THE LOCATION OF THE
LAND INVOLVED.

Attorneys (If Known)
Unknown

II. BASIS OF JURISDICTION (Select One Box Only)

- ☐ 1 U.S. Government Plaintiff ☒ 3 Federal Question (U.S. Government Not a Party)
- ☐ 2 U.S. Government Defendant ☐ 4 Diversity (Indicate Citizenship of Parties in Item III)

III. CITIZENSHIP OF PRINCIPAL PARTIES (Select One Box for Plaintiff and One Box for Defendant)

- | | PTF | DEF | | PTF | DEF |
|---|----------------------------|----------------------------|---|----------------------------|----------------------------|
| Citizen of This State | <input type="checkbox"/> 1 | <input type="checkbox"/> 1 | Incorporated or Principal Place of Business in This State | <input type="checkbox"/> 4 | <input type="checkbox"/> 4 |
| Citizen of Another State | <input type="checkbox"/> 2 | <input type="checkbox"/> 2 | Incorporated and Principal Place of Business in Another State | <input type="checkbox"/> 5 | <input type="checkbox"/> 5 |
| Citizen or Subject of a Foreign Country | <input type="checkbox"/> 3 | <input type="checkbox"/> 3 | Foreign Nation | <input type="checkbox"/> 6 | <input type="checkbox"/> 6 |

IV. NATURE OF SUIT (Select One Box Only)

CONTRACT	TORTS	FORFEITURE/PENALTY	BANKRUPTCY	OTHER STATUTES
<input type="checkbox"/> 110 Insurance <input type="checkbox"/> 120 Marine <input type="checkbox"/> 130 Miller Act <input type="checkbox"/> 140 Negotiable Instrument <input type="checkbox"/> 150 Recovery of Overpayment & Enforcement of Judgment <input type="checkbox"/> 151 Medicare Act <input type="checkbox"/> 152 Recovery of Defaulted Student Loans (Excl. Veterans) <input type="checkbox"/> 153 Recovery of Overpayment of Veteran's Benefits <input type="checkbox"/> 160 Stockholders' Suits <input type="checkbox"/> 190 Other Contract <input type="checkbox"/> 195 Contract Product Liability <input type="checkbox"/> 196 Franchise	PERSONAL INJURY <input type="checkbox"/> 310 Airplane <input type="checkbox"/> 315 Airplane Product Liability <input type="checkbox"/> 320 Assault, Libel & Slander <input type="checkbox"/> 330 Federal Employers' Liability <input type="checkbox"/> 340 Marine <input type="checkbox"/> 345 Marine Product Liability <input type="checkbox"/> 350 Motor Vehicle <input type="checkbox"/> 355 Motor Vehicle Product Liability <input type="checkbox"/> 360 Other Personal Injury PERSONAL INJURY <input type="checkbox"/> 362 Personal Injury - Med. Malpractice <input type="checkbox"/> 365 Personal Injury - Product Liability <input type="checkbox"/> 368 Asbestos Personal Injury Product Liability PERSONAL PROPERTY <input type="checkbox"/> 370 Other Fraud <input type="checkbox"/> 371 Truth in Lending <input type="checkbox"/> 380 Other Personal Property Damage <input type="checkbox"/> 385 Property Damage Product Liability	<input type="checkbox"/> 610 Agriculture <input type="checkbox"/> 620 Other Food & Drug <input type="checkbox"/> 625 Drug Related Seizure of Property 21 USC 881 <input type="checkbox"/> 630 Liquor Laws <input type="checkbox"/> 640 R.R. & Truck <input type="checkbox"/> 650 Airline Regs. <input type="checkbox"/> 660 Occupational Safety/Health <input type="checkbox"/> 690 Other	<input type="checkbox"/> 422 Appeal 28 USC 158 <input type="checkbox"/> 423 Withdrawal 28 USC 157 PROPERTY RIGHTS <input type="checkbox"/> 820 Copyrights <input type="checkbox"/> 830 Patent <input type="checkbox"/> 840 Trademark	<input type="checkbox"/> 400 State Reapportionment <input type="checkbox"/> 410 Antitrust <input type="checkbox"/> 430 Banks and Banking <input type="checkbox"/> 450 Commerce <input type="checkbox"/> 460 Deportation <input type="checkbox"/> 470 Racketeer Influenced and Corrupt Organizations <input type="checkbox"/> 480 Consumer Credit <input type="checkbox"/> 490 Cable/Sat TV <input type="checkbox"/> 810 Selective Service <input type="checkbox"/> 850 Securities/Commodities/Exchange
REAL PROPERTY <input type="checkbox"/> 210 Land Condemnation <input type="checkbox"/> 220 Foreclosure <input type="checkbox"/> 230 Rent Lease & Ejectment <input type="checkbox"/> 240 Torts to Land <input type="checkbox"/> 245 Tort Product Liability <input type="checkbox"/> 290 All Other Real Property	CIVIL RIGHTS <input type="checkbox"/> 441 Voting <input type="checkbox"/> 442 Employment <input type="checkbox"/> 443 Housing/Accommodations <input type="checkbox"/> 444 Welfare <input type="checkbox"/> 445 Amer. w/Disabilities - Employment <input type="checkbox"/> 446 Amer. w/Disabilities - Other <input type="checkbox"/> 440 Other Civil Rights	PRISONER PETITIONS <input type="checkbox"/> 510 Motions to Vacate Sentence Habeas Corpus: <input type="checkbox"/> 530 General <input type="checkbox"/> 535 Death Penalty <input type="checkbox"/> 540 Mandamus & Other <input type="checkbox"/> 550 Civil Rights <input type="checkbox"/> 555 Prison Condition	LABOR <input type="checkbox"/> 710 Fair Labor Standards <input type="checkbox"/> 720 <input type="checkbox"/> 730 <input type="checkbox"/> 740 <input type="checkbox"/> 790 <input type="checkbox"/> 791	SOCIAL SECURITY <input type="checkbox"/> 861 HIA (1395m) <input type="checkbox"/> 900 Appeal of Fee Determination Under Access to Justice <input type="checkbox"/> 950 Constitutionality of State Statutes

V. ORIGIN (Select One Box Only)

- ☒ 1 Original Proceeding ☐ 2 Removed from State Court ☐ 3 Remanded from Appellate Court ☐ 4 Reinstated or Reopened ☐ 5 Transferred from another district (specify) ☐ 6 Multidistrict Litigation ☐ 7 Appeal to District Judge from Magistrate Judgment

VI. CAUSE OF ACTION

Cite the U.S. Civil Statute under which you are filing (Do not cite jurisdictional statutes unless diversity):
35 U.S.C. Sections 271, 281

Brief description of cause:

Patent Infringement of U.S. Patent No. 5,818,630

VII. REQUESTED IN COMPLAINT:

☐ CHECK IF THIS IS A CLASS ACTION UNDER P.R.C.P. 23

DEMAND \$

CHECK YES only if demanded in complaint:

JURY DEMAND: ☒ Yes ☐ No

VIII. RELATED CASE(S) IF ANY

(See instructions):

JUDGE

DOCKET NUMBER

DATE

11-16-06

SIGNATURE OF ATTORNEY OF RECORD

[Signature] (P47839)

FOR OFFICE USE ONLY

RECEIPT # _____ AMOUNT _____ APPLYING IFP _____ JUDGE _____ MAG. JUDGE _____

TO LOCAL RULE 83.11

Is this a case that has been previously dismissed?

☐ Yes

☒ No

If yes, give the following information:

Court: _____

Case No.: _____

Judge: _____

2. Other than stated above, are there any pending or previously discontinued or dismissed companion cases in this or any other court, including state court? (Companion cases are matters in which it appears substantially similar evidence will be offered or the same or related parties are present and the cases arise out of the same transaction or occurrence.)

☐ Yes

☒ No

If yes, give the following information:

Court: _____

Case No.: _____

Judge: _____

Notes :
